March 1965

APPENDIX D

DIRECT DETECTION OF AMBIENT ELECTRON PLASMA OSCILLATION FIELDS IN THE MAGNETOSPHERE

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Recently, Huguenin, Lilley, McDonough and Papagiannis[1] reported on 700 kc/s and 2.2 Mc/s radio noise measurements made on 30 July, 1963 at altitudes between 3000 and 11,000 km from a high-altitude rocket probe. They found a relatively high background brightness at 700 kc/s, and several intense noise bursts were also observed. It was suggested that non-thermal source mechanisms such as harmonic gyro radiation and EM radiation from plasma waves could contribute to the high 700 kc/s background, and radiation from relativistic electrons was considered as the source of one of the noise bursts (event A which appeared in both channels near the geomagnetic equator). However, Huguenin, et.al., observed that event D, the most intense noise burst $[b_{max} \approx 8 \times 10^{-17}$ W M^{-1} $(c/s)^{-1}$, duration $\approx$ 800 sec$]$ appeared only in the lower channel and at an altitude ($h \cong 4600 \pm 1500$ km) for which the local electron plasma frequency approached 700 kc/s.

In this note we wish to discuss a possible interpretation of event D. Specifically, we suggest that the antennas were simply responding to the electrostatic fields associated with the thermal or equilibrium level of electron plasma oscillations, rather than to any local resonance. If the geomagnetic field is ignored and the distribution functions are

Maxwellian, the wave fields are described by[2]

$$\underset{\sim}{E} = - \nabla \phi \quad , \quad \phi = \phi_o \exp i(\underset{\sim}{k} \cdot \underset{\sim}{r} - \omega t) \quad , \tag{1}$$

with $\omega = \omega_1 - i\omega_2$ and

$$\left.\begin{aligned} \omega_1^{\,2} &= \omega_p^{\,2}(1 + 3k^2/K_D^{\,2} + \ldots) \\ \omega_2 &= (\pi/8)^{\frac{1}{2}}\, \omega_p\, (K_D/k)^3 \exp(-K_D^{\,2}/2k^2) + \ldots \end{aligned}\right\} \; 0 < k < K_D \tag{2}$$

Here $\omega_p^{\,2} = 4\pi Ne^2/m$, $ma^2 = 2\kappa T$, $K_D^{\,2} = 2\omega_p^{\,2}/a^2$ and the imaginary term represents Landau damping. If the plasma is in equilibrium and the temperature is finite, the thermal motion gives rise to a non-vanishing level for the plasma oscillations. Rostoker[3] has shown that a form of equipartition which takes into account Landau damping leads to the following expression for the equilibrium fields:

$$\frac{\langle E^2 \rangle}{8\pi} = \frac{1}{(2\pi)^3} \int d\underset{\sim}{k}\; \frac{\kappa T}{2}\; \frac{K_D^{\,2}}{(k^2 + K_D^{\,2})} \quad . \tag{3}$$

In the presence of a magnetic field, Eqs. (1), (2) remain strictly valid only for propagation parallel to B, and hence Eq. (3) requires modification. However, Bernstein has demonstrated[4] that weak field corrections to the dispersion relation involve terms of order $(\omega_c/\omega_p)^2$ and Fig. (3) of Huguenin, et.al., shows that $(\omega_c/\omega_p)^2 \approx 0.08$ at the peak of the noise burst. We therefore neglect this correction and apply Eq. (3) to study event D.

The two ten-meter antenna elements were coupled to form a balanced dipole and the probe was relatively inefficient as a detector of modes with $\lambda_{\parallel} \lesssim \lambda_o \simeq$ (10-20) meters. We approximate the response by integrating only over the range $0 < k < k_o = 2\pi/\lambda_o$ for k parallel to the dipole and Eq. (3) becomes

$$E_B^2 = \langle E^2 \rangle \approx \frac{2}{\pi} \kappa T_e \int_o^{K_D} k_\perp dk_\perp \int_o^{k_o} dk_\parallel \frac{K_D^2}{k_\perp^2 + k_\parallel^2 + K_D^2} \tag{4}$$

$$\approx \frac{\kappa T_e K_D^2 k_o}{\pi} \ln 2 \quad . \tag{5}$$

At the altitude of 4500 km, $\omega_1 \simeq \omega_p \simeq 2\pi(7 \times 10^5)$ gives $N_e \simeq 6 \times 10^3$ cm^{-3}, and for $T_e \simeq 3 \times 10^3$ ^{o}K, $K_D \simeq 0.2$ cm^{-1}. If λ_o is 20 meters, Eq. (5) yields

$$\begin{aligned} E_B &\simeq 3.4 \times 10^{-9} \text{ esu/cm} \\ &\simeq 100 \text{ microvolts/meter} \quad , \end{aligned} \tag{6}$$

as the predicted equilibrium level of the electron plasma oscillation field with $k_\parallel \lesssim k_o$. This prediction does not take into account the relatively narrow receiver bandwidth ($\Delta\nu \simeq 14$ kc/s in the 700 kc/s channel) and thus Eq. (4) certainly overestimates the background field which should be observed. However, Eq. (2) may be used to show that the group velocity for the electron plasma oscillation is on the order of

$$\left(\frac{d\omega}{dk}\right)_{\omega_p} \simeq \left(\frac{3ka}{2\omega_p}\right) a + \ldots \tag{7}$$

and v_g can be sufficiently low so that Doppler shifts increase the effective bandwidth significantly. For $T_e \simeq 3 \times 10^3$ ^oK, a $\approx$ 300 km/sec is very large compared to the probe speed but $k_o a/\omega_p \approx 0.02$, and $(d\omega/dk)$ can then have a maximum value of about 10^6 cm/sec for certain probe orientations. Sheath effects, and inclusion of geomagnetic field corrections to Eq. (3) must also be considered, and hence the significance of the absolute value for E_B is quite questionable.

In spite of these uncertainties it seems plausible that event D is describable in terms of detection of the ambient electrostatic fields. The relationship between flux, bandwidth and Thévenin open circuit voltage (e_a) given by Huguenin, et.al., is

$$\bar{b} \simeq 2.4 \times 10^{-5} \left(\frac{e_a^2}{\Delta\nu}\right) W\ M^{-1}\ (c/s)^{-1}/\text{ster} \quad , \tag{8}$$

and for a solid angle near 4π, a flux of 8×10^{-17} W M^{-1} $(c/s)^{-1}$ was measured. This gives $e_a \simeq 6 \times 10^{-5}$ volts. With an effective length of 10 meters, the indicated electric field in the antenna is thus on the order of $6\mu V/M$ or a factor of 16 below the uncorrected equilibrium value of Eq. (6). Furthermore, it is worth noting that the observed value for e_a is a factor of 4000 smaller than $\kappa T/e$, a reasonable estimate of the largest amplitude for an electrostatic wave in a plasma under non-equilibrium conditions. This observation is relevant because DC electric fields, currents, thermal anisotropies and inhomogeneities can all serve to reduce the Landau damping and allow the waves to attain large non-equilibrium amplitudes. Indeed, recent VLF electric field measurements[5] on the spacecraft 1964-45A reveal that when finite bandwidth corrections, sheath effects and Doppler broadening are taken into account, Eq. (3) does yield an adequate description of the background level, assuming that the waves are electrostatic ion oscillations $[0 < \omega < \omega_p(\text{ion})]$. However, VLF field enhancements by factors of (5-50) over the background value were customarily encountered, and it therefore seems reasonable to suppose that the rocket probe antennas were simply sampling the ambient near-equilibrium values for electron plasma oscillation fields during event D.

ACKNOWLEDGEMENT - This work was supported in part by the National Aeronautics and Space Administration under Contract NASw-698.

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